Channel widening during extreme floods: how to integrate it within river corridor planning ?

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ABSTRACT

Channel widening taking place during large flood events can be substantial in mountain rivers, with consequent great potential damages to infrastructures and buildings. The purpose of this work is twofold: i) to provide a quantitative assessment of geomorphic effects of an extreme flood event (recurrence interval > 100 years); ii) to test on this study case a new hydromorphological methodological framework (IDRAIM) developed to guide river corridor planning and management.

As to the first objective, field surveys were integrated with remote sensing, GIS and statistical analyses for a flood event occurred in 2011 in Northwestern Italy. Channel widening ratios (width after / width before the flood) were calculated and then correlated with different controlling factors, and envelope relationships were then obtained.

The tool of the IDRAIM framework used for the second objective was the Event Dynamics Classification (EDC) applied to selected study reaches, whose widening ratios turned out to correspond well with the EDC classes.

Based on the results obtained, a practical procedure for predicting the expected widening is finally proposed.

KEYWORDS

large floods; channel changes; stream power; bank erosion; river corridor

INTRODUCTION

Infrequent, high-magnitude floods can lead to sudden, dramatic channel changes in alluvial and semi-alluvial channels. Indeed, the geomorphic role of large floods has long been debated (e.g. Wolman and Miller, 1960; Costa and O'Connor, 1995; Phillips, 2002; Magilligan et al., 2015). Nonetheless, rather few are the studies which have analyzed in detail the magnitude of channel widening determined by extreme floods in Alpine rivers (Krapesch et al., 2011), despite the paramount relevance of such process on flood hazard. In fact, a sound river corridor planning should include – beside flood inundation depth and velocities – the expected channel dynamics (bank erosion and bed incision/aggradation) occurring during

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flood events, as these can both substantially modify the flooding pattern and cause direct damage to buildings and infrastructures.
Unfortunately, the expected sudden and notable changes in channel width during floods are typically not included in flood hazard mapping. Indeed, our current understanding of the factors controlling channel widening is very limited. In fact, hydrodynamic forces were found to be not sufficient to explain geomorphic effects (e.g. Heritage et al., 2004; Nardi and Rinaldi, 2015), and thus other factors, such as bedload supply and pre-flood channel planform (Dean and Schmidt, 2013), lateral confinement (Thompson and Croke, 2013), and channel curvature (Buraas et al., 2014) should also be also accounted for in the prediction of widening. However, field data available to build reliable statistical models or to validate numerical morphodynamic models are very limited. On the other hand, easy-to-use tools applicable by practitioners of river management agencies are much needed to predict the reach-scale morphological response of the channel network to extreme (recurrence intervals RI>100 yr) flood events.

The purpose of this work is twofold: i) to provide a quantitative assessment of the channel widening associated to an extreme flood event which occurred in 2011 in Northwestern Italy (Magra River basin); and ii) to test on this study case a new methodological framework (IDRAIM) developed to guide river corridor planning and management which focuses on channel adjustments occurring both in the long-term and during extreme events.

METHODS

Study case: the 2011 flood event in the Magra River basin

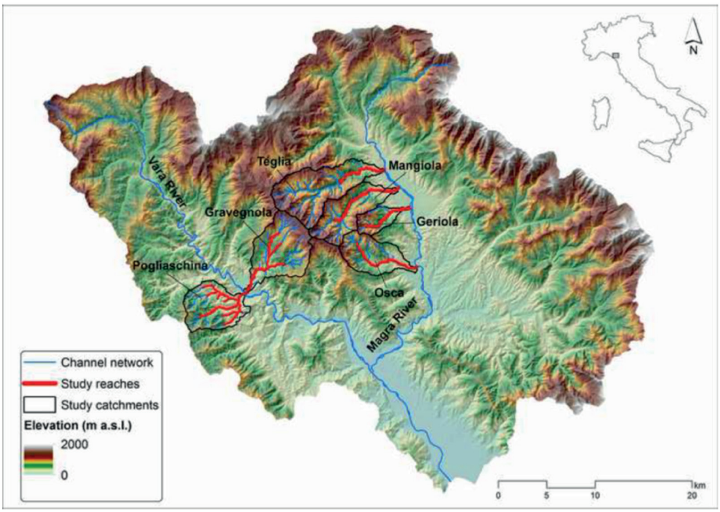

Figure 1: Location map of the Magra River basin and of the analyzed tributaries (from Surian et al., 2016).

The Magra River basin is located in the northern Apennines (Italy) and covers an area of 1717 km², ranging from sea level to a maximum elevation of 1901 m a.s.l. (Fig. 1). Sedimentary rocks (mostly sandstones and mudstones) prevail in the basin, but some outcrops of magmatic (ophiolites) and metamorphic rocks are also present. The climate is Mediterranean, with dry summers and the most abundant precipitation occurring in autumn. The mean annual precipitation is about 1700 mm, and maximum values (up to about 3000 mm) are observed in the upper part of the catchment. Forests cover 66% of total basin area and occupy most of catchments slopes. Agricultural areas, urban areas and transportation structures mostly lie in the valley floors and on the lower sectors of the slopes.
An intense precipitation event took place within the river basin on October 25th, 2011, and originated a flash flood both in the Magra River, with a peak discharge having a RI of about 100 yr (Nardi and Rinaldi, 2015) and along several tributaries, there with extremely high peak flows (up to RI>300 yr, based on rainfall time series), where enormous volumes of large wood were eroded from the floodplains (Lucía et al., 2015) causing extensive bridge clogging. Rainfall maps for the study event were obtained based on data from a rain gauges network and the Monte Settepani radar, and the estimates show that maximum hourly rates were up to 149 mm/hr, whereas three-hours maximum and event-accumulation maxima were up to 326 mm and 500 mm, respectively. Antecedent moisture conditions in the basins were intermediate. An integrated approach was adopted to investigate the geomorphic effects of the 2011 flood in the Magra catchment, and the whole approach is described in detail by Rinaldi et al. (2016).

Six catchments chosen among those where rainfall was most intense were selected to analyze channel response: Pogliaschina, Gravegnola, Osca, Teglia, Geriola and Mangiola (Fig. 1).

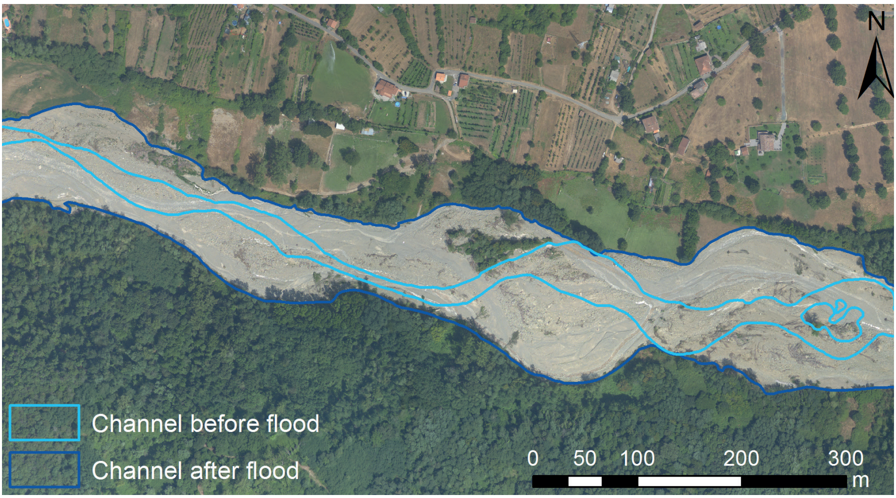

Figure 2: Example of the channel widening observed in the Mangiola River.

In these rivers, unit peak discharge estimates range from 12.8 $m^3s^{-1}km^{-2}$ (Osca) to 23.7$m^3s^{-1}km^{-2}$ (Pogliaschina). Streams within the six catchments are characterized by average channel slope ranging from 4.1% (Osca) to 8.8% (Geriola), coarse sediments (mainly gravels and cobbles), and a wide range of conditions in terms of lateral confinement, but only partly- and unconfined reaches were analyzed for channel widening. Importantly, artificial structures (bed and bank protections) were very limited before the flood.
The morphological changes induced by the 2011 flood were assessed by field surveys and interpretation of aerial photographs. To assess changes in channel width, channel banks and islands (i.e. in-channel surfaces covered by woody vegetation) were digitized on pre- and post-flood orthophotos (Fig. 2). The term "channel" refers to the active channel, which includes low-flow channels and unvegetated or sparsely vegetated bars (i.e. exposed sediments). Then, channel width was calculated dividing channel area by the length of the reach, and changes in channel width were expressed as width ratio Wr, i.e. channel width after / channel width before the flood, as in Krapesch et al. (2011).

The IDRAIM methodological framework

The IDRAIM methodological framework (Rinaldi et al., 2014, 2015) includes the following four phases: (1) catchment-wide characterization of the fluvial system; (2) evolutionary trajectory reconstruction and assessment of current river conditions; (3) description of future trends of channel evolution; (4) identification of management options. A series of specific tools have been developed for the assessment of river conditions, in terms of morphological quality and channel dynamics. These latter include the "Morphological Dynamics Index", the "Event Dynamics Classification", and the "River Morphodynamic Corridors".
The present work focuses specifically on the "Event Dynamics Classification" (EDC), applying it to selected study reaches and comparing them with observed geomorphic changes. In particular, EDC leads to classify each reach into one of four classes of expected event dynamics (very high, high, medium, low), adopting a guided logical procedure based on flow charts. The assessment is carried out by combining two aspects (Table 1):

Table 1: Classification of EDC (Event Dynamics Classification, from low to very high) based on the expected morphological changes (from small to very relevant) coupled to the clogging probability (From Rinaldi et al., 2015).

		Clogging probability	
		High (H)	Low (L)
Expected morphological changes	Very relevant (I)	Very high	Very high
	Relevant (II)	Very high	High
	Intermediate (III)	High	Medium
	Small (IV)	Medium	Low

i) the expected magnitude of morphological changes (4 classes) and ii) the clogging conditions (2 classes, i.e. likely or not likely occurrence of clogging, mostly by wood elements) at critical cross-sections (bridges and culverts). EDC provide information on the expected magnitude of channel dynamics in a given reach on a one-dimensional scale. This information has to be integrated with a 2-D analysis to define the areas of the fluvial corridor that will be affected by such dynamics (“Event Morphodynamic Corridor”, EMC). The procedure suggested in IDRAIM for the delineation of the event river morphodynamic corridor (EMC) includes (i) reconstruction of historical channel changes; (ii) determining the expected flood spatial dynamics based on EDC class; iii) identification of natural elements of confinement (e.g., hillslopes, old terraces); and (iv) identification of reliable protection works preventing lateral channel mobility. All the details of the methodology for both EDC and EMC can be found in Rinaldi et al. (2014 and 2015).

RESULTS

Channel widening in the Magra River basin

The “Width Ratio” (Wr) measured in all the analyzed reaches (n=157) of the six basins described above are plotted in Figure 3 against the estimated unit stream power of the flood peak, calculated using the pre-event channel width (as in Krapesch et al., 2011) as $\omega = \gamma QS/W$, where γ is the specific weight of water, Q is the flood peak discharge, S is channel slope, and W is the channel width measured before the flood. The unit stream power estimated using the pre-event width was found to lead to better statistical results compared to its calculation through the post-event width (Surian et al., 2016).
The widening data (n=35) measured in the main channel of the Magra River (Nardi and Rinaldi, 2015) are reported as well. The large variability (log-log scale graph) of the channel response to similar flow energy is clearly apparent, especially at intermediate unit stream power (1000-10000 Wm^{-2}). The best fit (R^2 = 0.44) power equation including all data is the following:

$$W_r = 0.07\omega^{0.44}$$

Equation 1

Based on this regression, the minimum unit stream power required to cause some widening turns out to be about 400 Wm^{-2}. However, one reach of the Magra River exhibited a width ratio of 1.08 for a unit stream power as low as 173 Wm^{-2}. On the other side, very limited widening (Wr<1.1) was observed in some reaches for ω up to about 5000 Wm^{-2}. Very intense channel widening (Wr>10) was instead observed for ω>2000 Wm^{-2} in other reaches (Graveg-nola, Pogliaschina, Osca channels). As a consequence of the enormous scatter in the relationship, indications on the maximum expected width ratios are sounder to plan on the safety side. To this aim, the following equation (dashed line in Fig. 3) represents the upper envelope of the plot, fitted to a linear trend excluding the seemingly outliers (9 out of 192 reaches, i.e. about 5%):

$$W_r \approx 0.002\omega$$

Equation 2

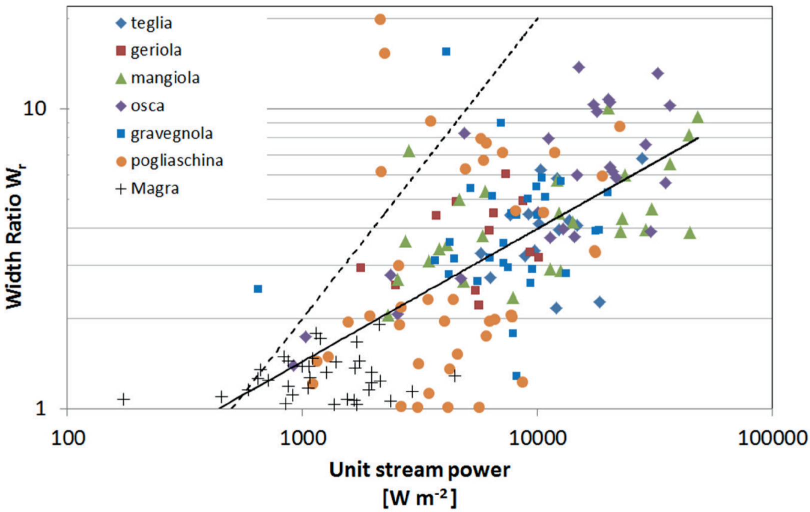

Figure 3: Scatterplot of width ratio vs unit stream power (calculated based on the pre-event channel width) for the study reaches. Data from Nardi and Rinaldi (2015) are also included. The solid line represents the best fit equation (Eq. 1), the dashed line the upper envelope curve (Eq. 2).

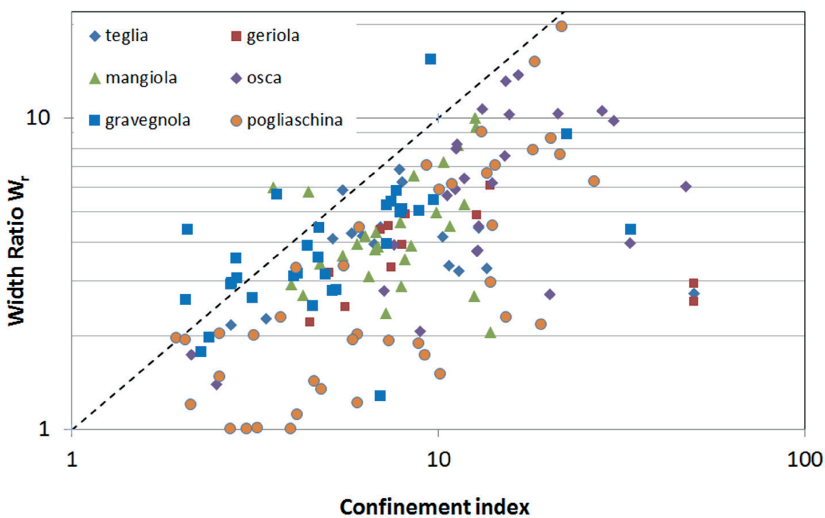

Figure 4: Scatterplot of width ratio vs confinement index (i.e. alluvial plain width / pre-event channel width) for the study reaches. Data from Nardi and Rinaldi (2015) are not available. The dashed line represents the 1:1 relationship.

Nonetheless, the lateral confinement (expressed by the confinement index calculated as alluvial plain width divided by pre-event channel width) plays a relevant role on the maximum width ratios, as shown in Figure 4, where most of the data plot below – in some cases considerably – the equality line. However, 10 reaches feature widening ratios exceeding the confinement index, an indication that part of the hillslopes was also eroded during the flood (this was verified in the field). Therefore, in most of cases the widening was not limited by the lateral extent of the erodible corridor, although a positive correlation exists between the two variables.
When plotting the widening magnitude against the pre-flood channel width, an inverse relationship is shown (Fig. 5). The plot shows how large is the variability in the width ratios observed in the narrower (1-10 m) reaches, and that for large channels (>100 m) width ratios > 1.5 should not be expected.

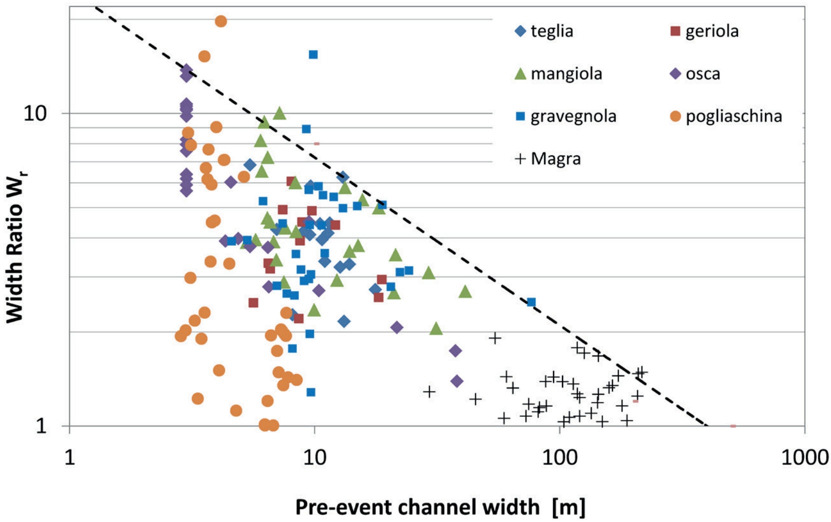

Figure 5: Scatterplot of width ratio vs pre-event channel width for the study reaches. Data from Nardi and Rinaldi (2015) are also included. The dashed line represents equation 3 (envelope curve).

The envelope curve (fitted by eye to a simple power form, excluding 5% of the dataset) is given by following equation:

$$W_r \approx 25 W_b^{-1/2}$$

Equation 3

A more complete, in-depth statistical analysis – entailing multiple factors – for the understanding of the variability in the observed width ratios is presented in Surian et al. (2016), whereas the practical prediction of the widening extent is discussed in the next section.

Table 2: EDC (Event Dynamics Classification), width ratio and basic characteristics of some reaches of the Magra and Mangiola rivers..

River reach	Confinement class	Slope	Expected morphological changes	Clogging probability	EDC class	Width ratio
Magra 3_1	Partly confined	0.016	Intermediate	Low	High	1.3
Magra 3_8	Unconfined	0.006	Relevant	High	Very high	1.6
Magra 6_3	Unconfined	<0.001	Intermediate	Low	Medium	1.0
Mangiola 2_2	Partly confined	0.037	Very relevant	High	Very high	3.5
Mangiola 2_3	Unconfined	0.049	Very relevant	High	Very high	5.3

Predicting channel widening based on morphological analysis

The "Event Dynamics Classification" (EDC) was applied to some reaches of the Magra and Mangiola rivers, as a preliminary test. Table 2 presents the EDC classification along with the width ratio measured after the 2011 flood event.

The partly confined reach classified as "Very high" event dynamics (the highest, indicating that flood waters and bedload transport are expected to abandon the existing channel as a result of avulsion processes related to relevant aggradation, landslide damming or bridge clogging) featured a widening of 3.5, much higher than the one falling into "High" class (Wr=1.3). For the unconfined reaches, the lowest slope Magra reach (close to the river outlet) classified with "Medium" dynamics (a class indicating that avulsions are not expected, and only local bank erosions and limited aggradation or incision are expected) showed no widening during the 2011 event, whereas a "Very high" dynamics was attributed to the steeper reach in the Mangiola which was characterized by Wr=5.3.

DISCUSSION AND CONCLUSIONS

The magnitude of the channel widening occurred during the 2011 flood in the Magra River basin is hugely variable, and the relevance and significance of the different factors (including unit stream power, confinement index and sediment supply as well) are mediated by channel slope, as statistically demonstrated in Surian et al. (2016). A simplified approach to a first order estimation of the average extent of the widening expected during a large (RI>100 yr) flood in mountain basins could be based on the upper envelope curves for the observed width ratios, with the caution that our database is limited to one river basin (although large and diverse) and to one event. The procedure should entail: i) application of eqs. 2-3 and averaging of their results, in order to derive the maximum potential width ratio based on flow energy/channel size; ii) assessment of the confinement index; iii) evaluation of EDC class.

In case the Wr estimated by the integrated application of eqs. 2-3 is larger than the confinement index, and the EDC class is "high" or "very high" (meaning that artificial bank protections are not present, not reliable or not relevant for the event dynamics), the Wr should be assumed equal to the confinement index, or even slightly higher in case of poorly resistant hillslope substrates. In case EDC is high or very high, but the confinement index is larger than what predicted by Eqs. 2-3, then the latter values should be adopted. Finally, if EDC classes are low to medium (due to either stable bank protections, or cohesive banks/very low slopes), the potential for widening is limited, and the width ratios predicted by eqs. 2-3 should be considered unrealistic, and a very limited widening (even null) could be assumed. Further post-event analysis will be obviously of great importance to broaden the dataset and to test the suggested simplified approach.

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